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Summary of WG 4: Mixing and mixing-related CP violation in the B system

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We present the summary of the working group on B mixing and the related CP violation at the CKM 2014 workshop. The contributions reflect the experimental and theoretical progress in the field over the last two years since the last CKM workshop.

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1 Introduction

Mixing and CP violation in the B system have been essential in establishing the Cabibbo-Kobayashi-Maskawa (CKM) picture of flavour- and CP violation in the Standard Model (SM) [1], as exemplified by the successful fits to the Unitarity Triangle (UT) [2, 3, 4, 5, 6],* and continue to provide important constraints on SM parameters and new physics (NP) models, some of which are discussed in the following.

The present article summarizes 21 contributions, grouped according to the section topics “ B mixing and b -hadron lifetimes”, “Determination of the mixing phases $\phi_{d,s}$ ”, and “Determination of the UT angles $\alpha(\phi_2)$ and $\gamma(\phi_3)$ ”.

2 B mixing and b-hadron lifetimes

The mixing of neutral mesons with their antiparticles can be characterized by three quantities: $|M_{12}|$, $|\Gamma_{12}|$, and $\phi_{12} = \arg(-M_{12}/\Gamma_{12})$, all related to measurable quantities, see Ref. [8] for details and further references.[†] M_{12} is related to the dispersive part of the transition amplitude $\langle B|\mathcal{H}|\bar{B}\rangle$; this quantity is sensitive to heavy particles in the loop, *i.e.* the top quark in the SM and potential new particles in NP models. On the other hand, Γ_{12} is determined from the absorptive part of the same amplitude, and thereby less sensitive to NP.

The calculation of these quantities in the SM is facilitated by large hierarchies: the fact that M_{12} is dominated by contributions from heavy internal particles allows for using an effective field theory with only one effective four-quark operator, the coefficient of which can be computed reliably in perturbation theory [9, 10]. The corresponding hadronic matrix element is accessible on the lattice, as are the ones for the operators appearing in NP models, with uncertainties at the few-percent level, see Ref. [11] for a recent review. The calculation of Γ_{12} is more involved, since lighter degrees of freedom are relevant; a second operator product expansion is necessary, the so-called heavy quark expansion (HQE), which exploits a second hierarchy, $m_b \gg \Lambda_{\text{QCD}}$, see *e.g.* Ref. [12] for details and references. The precision of these calculations is presently around 20%, limited by the remaining non-perturbative parameters [8]. Several discrepancies between experimental results and HQE predictions used to question the validity of the HQE; these have been resolved over the last years, most recently with high-precision results from the LHC experiments, see Refs. [8, 13] and the discussion below, yielding a very consistent picture. A remaining puzzle is the measurement of a relatively large like-sign dimuon asymmetry (LSDA) by the D0 collaboration [16, 17], discussed below and in [18, 19, 20].

*The long-standing tension between the inclusive and exclusive extraction of the CKM matrix elements V_{ub} and V_{cb} is discussed in more detail in WG 2 [7].

[†]Note that the convention used here is slightly different from [8]: the additional index ‘12’ is added here, because $\phi_{d,s}$ is used below for the phase appearing in time-dependent $B_{d,s}$ decays.

From an experimental point of view, the determination of b -hadron lifetimes has evolved from early measurements by the CLEO and LEP experiments to precision measurements by the B -factories and the Tevatron experiments; recently, the LHCb Collaboration further improved the precision of these earlier measurements significantly for all weakly decaying b -hadrons, up to an order of magnitude in some cases [13]. This was possible using about 3 fb^{-1} of collected proton-proton collision data delivered by the LHC at 7 and 8 TeV center-of-mass energy in 2011 and 2012, respectively. Hadron colliders benefit from two major advantages, the large production cross-section of b -quarks and the production of all species of b -hadrons in the hadronization process. However, the challenge for them is to cope with an extremely large data rate. The trigger system reduces this rate to amounts that can be written on disk. Throughout the selection of the b -candidates of interest in the trigger system and during further processing, for example the track reconstruction, some quantities like the impact parameter of the b -candidate will distort and/or bias the distribution of the decay-time acceptance. To overcome these experimental issues, two possible approaches can be adopted. The first one is to perform absolute lifetime measurements, which is harder experimentally. While typically modes with large branching fractions can be used, leading to a good statistical precision, this approach requires an excellent knowledge of all the small systematic effects that contribute to the distortion of the observable of interest, *i.e.* the lifetime. The alternative is to perform relative lifetime measurements. They rely on the fact that most of the systematic effects will cancel in the lifetime ratio. LHCb has applied both approaches and the various analyses are summarized in the following.

With 1 fb^{-1} of collected data LHCb performed the most precise absolute lifetime measurements to date for $B_{d,s}^0$, B^- and Λ_b^0 , exploring decays involving a J/Ψ [21]. The modes in question are: $B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^*(892)^0$, $B^0 \rightarrow J/\psi K_S^0$, $B_s^0 \rightarrow J/\psi \phi$ and $\Lambda_b^0 \rightarrow J/\psi \Lambda$. The results are reported in Table 1. Additionally, as suggested in Ref. [22], a combined analysis of both $B^0 \rightarrow J/\psi K^*(892)^0$ and $B^0 \rightarrow J/\psi K_S^0$ together with the knowledge of the mixing phase $\beta = (21.5_{-0.7}^{+0.8})^\circ$ [23] allows for the measurement of $\Delta\Gamma_d/\Gamma_d$, which can be used as a probe for NP searches as *e.g.* argued in Ref. [8]. However, the measured value was found to be $\Delta\Gamma_d/\Gamma_d = -0.044 \pm 0.025_{\text{(stat)}} \pm 0.011_{\text{(syst)}}$, consistent with SM predictions.

The abundant, yet previously unobserved $\Lambda_b^0 \rightarrow J/\psi p K$ mode provides the most precise measurement of the lifetime ratio $\tau_{\Lambda_b}/\tau_{B^0}$ to date. Using 3 fb^{-1} , the lifetime of Λ_b^0 was measured to be $1.479 \pm 0.009_{\text{(stat)}} \pm 0.010_{\text{(syst)}} \text{ ps}$ [14]. This measurement is compatible with other recent measurements of this quantity (like the one above, see Ref. [23] and references therein) as well as with the HQE prediction [12]. Therefore the long-standing puzzle of this ratio being measured lower than expected from theory has been resolved.

In two LHCb analyses with 3 fb^{-1} the relative lifetimes of b -baryons containing strange quarks were improved and confronted with their theoretical predictions

Lifetime	Value [ps]
$\tau_{B^+ \rightarrow J/\psi K^+}$	$1.637 \pm 0.004 \pm 0.003$
$\tau_{B^0 \rightarrow J/\psi K^{*(892)0}}$	$1.524 \pm 0.006 \pm 0.004$
$\tau_{B^0 \rightarrow J/\psi K_S^0}$	$1.499 \pm 0.013 \pm 0.005$
$\tau_{\Lambda_b^0 \rightarrow J/\psi \Lambda}$	$1.415 \pm 0.027 \pm 0.006$
$\tau_{B_s^0 \rightarrow J/\psi \phi}$	$1.480 \pm 0.011 \pm 0.005$

Table 1: Fit results for the B^+ , B^0 , B_s^0 mesons and Λ_b^0 baryon lifetimes measured at LHCb [21]. The first uncertainty is statistical and the second is systematic.

from HQE. The Ξ_b^0 lifetime was measured for the first time [24], using the hadronic decay mode $\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$, resulting in $\tau_{\Xi_b^0 \rightarrow \Xi_c^+ \pi^-} = 1.477 \pm 0.026(\text{stat}) \pm 0.014(\text{syst}) \pm 0.013(\text{input})$ ps. The Ξ_b^- and Ω_b^- lifetimes were measured reconstructing a dimuon (J/ψ) and a hyperon (Ξ^-, Ω^-) in the final state [25] and were found to be $\tau_{\Xi_b^- \rightarrow J/\psi \Xi^-} = 1.55_{-0.09}^{+0.10}(\text{stat}) \pm 0.03(\text{syst})$ ps and $\tau_{\Omega_b^- \rightarrow J/\psi \Omega^-} = 1.54_{-0.21}^{+0.26}(\text{stat}) \pm 0.05(\text{syst})$ ps. The results agree again very well with the HQE estimate $\tau_{\Xi_b^0}/\tau_{\Xi_b^+} = 0.95 \pm 0.06$ [12] and are in the case of the Ω_b within the range of earlier estimates.

While in the B^0 system the width difference between the heavy and light mass eigenstates is predicted to be tiny and measured compatible with zero, see above, this is not the case for the B_s^0 system. This affects branching ratio measurements and opens the possibility to access the rate asymmetry and the width difference via the effective lifetime [26],

$$\tau_f^{\text{eff}} = \frac{\int_0^\infty dt \, t \langle \Gamma(B_s(t) \rightarrow f) \rangle}{\int_0^\infty dt \langle \Gamma(B_s(t) \rightarrow f) \rangle} = \frac{\tau_{B_s}}{1 - y_s^2} \frac{1 + 2\mathcal{A}_{\Delta\Gamma}^f y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^f y_s}, \quad (1)$$

where $y_s = \Delta\Gamma_s/(2\Gamma_s)$. In the SM decays such as $B_s^0 \rightarrow K^+ K^-$ and $B_s^0 \rightarrow D_s^+ D_s^-$ have tiny CP asymmetries, which is reflected in the predictions $\mathcal{A}_{\Delta\Gamma}^{B_s \rightarrow K^+ K^-} = -0.97_{-0.009}^{+0.004}$ [15] and $\mathcal{A}_{\Delta\Gamma}^{B_s \rightarrow D_s^+ D_s^-} = -1 + \mathcal{O}(10^{-3})$ [27]. Therefore the measurement of the effective lifetime of these modes is equivalent to measuring Γ_L . The lifetimes of both channels were measured using 1 and 3 fb $^{-1}$, respectively, and found to be $\tau_{B_s \rightarrow K^+ K^-}^{\text{eff}} = 1.407 \pm 0.016(\text{stat}) \pm 0.007(\text{syst})$ ps and $\tau_{B_s \rightarrow D_s^+ D_s^-}^{\text{eff}} = 1.379 \pm 0.026(\text{stat}) \pm 0.017(\text{syst})$ ps. Finally, in flavour-specific B_s^0 decays $\mathcal{A}_{\Delta\Gamma}^{fs} = 0$ holds, yielding a direct measurement of Γ_s^{-1} to first order in y_s . In particular, the measurements of the abundant hadronic $B_s^0 \rightarrow D_s \pi$ and semi-leptonic $B_s^0 \rightarrow D_s \mu \nu$ modes have been updated by both the LHCb and the D0 experiments [28, 29], reaching a statistical uncertainty of $\mathcal{O}(10)$ fs. The global picture of the effective lifetime measurements in the B_s^0 system, depicted in Fig. 1, shows good consistency. The measurement of $\Gamma_s, \Delta\Gamma_s$ from $B_s \rightarrow J/\psi K K$ decays, dominating the average, will be discussed later in the context of the determination of the mixing angle ϕ_s .

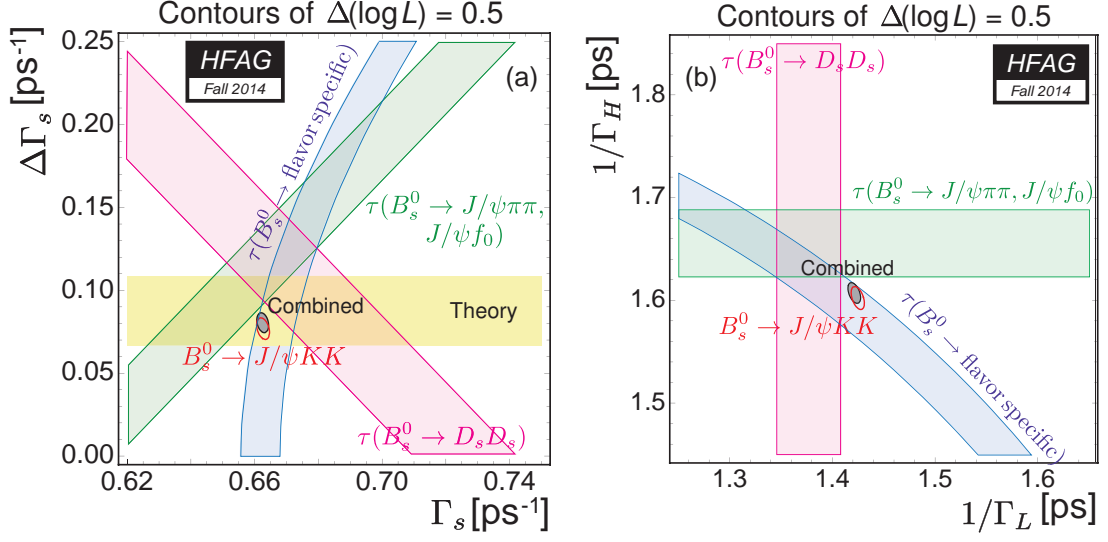


Figure 1: Available measurements of $\Gamma_s, \Delta\Gamma_s$ in the $\Delta\Gamma_s$ vs. Γ_s (left) and Γ_L vs. Γ_H (right) planes.

The mixing structure described in the beginning is very general, it holds also in the presence of NP. A simple model-independent parametrization of NP effects then reads $M_{12}^q = M_{12}^{q, \text{SM}} \Delta_q$, with complex parameters Δ_q , while Γ_{12} used to be considered SM-like [30]. Detailed analyses of this type have been carried out over the years [31]; at the moment, the results are perfectly compatible with the SM [8, 4, 5]. Albeit room is left for NP influence of about 20%, this translates into stringent limits on the generic scales of NP operators, typically much higher than directly accessible at colliders [4, 5]. Given the absence of large NP effects in M_{12} , the increasing experimental precision for the observables involved, and the fact that the LSDA cannot be explained in a fit with Δ_q only, there has been an increased interest in considering NP in Γ_{12}^q . Regarding $\Delta\Gamma_q$, for $q = s$ the relative influence is already bound to be below approximately 30% [32], while it can still be large for $q = d$ [8, 33]; $b \rightarrow d\tau^+\tau^-$ transitions are especially interesting in that respect and could still show a large enhancement.

The CP asymmetry in mixing of neutral B decays can be measured via decays to flavour-specific final states (typically semileptonic ones),

$$a_{\text{fs}} = a_{\text{sl}} = \frac{\Gamma[\overline{B}(\rightarrow B) \rightarrow f] - \Gamma[B(\rightarrow \overline{B}) \rightarrow \overline{f}]}{\Gamma[\overline{B}(\rightarrow B) \rightarrow f] + \Gamma[B(\rightarrow \overline{B}) \rightarrow \overline{f}]} = \left| \frac{\Gamma_{12}^q}{M_{12}^q} \right| \sin \phi_{12}^q. \quad (2)$$

It is expected to be very small in the SM, below the present level of experimental precision. It could however be enhanced in the presence of NP entering the mixing amplitude.

Recently, the LHCb experiment measured the asymmetries in both B^0 and B_s^0

systems [34, 35]: $a_{sl}^s = [-0.06 \pm 0.50(\text{stat}) \pm 0.63(\text{syst})]\%$ and $a_{sl}^d = [-0.02 \pm 0.19(\text{stat}) \pm 0.30(\text{syst})]\%$. Also the BaBar experiment presented at this workshop a new measurement using dimuon events from the full BaBar dataset of $471 \times 10^6 B\bar{B}$ pairs, yielding $a_{sl}^d = (-3.9 \pm 3.5(\text{stat}) \pm 1.9(\text{syst})) \times 10^{-3}$ [36, 37]. Both LHCb and BaBar measurements show an excellent agreement with the SM predictions. However, as shown in Fig. 2, some tension still remains with the measurement of the LSDA performed by D0 [17], $A_{CP} = (-0.235 \pm 0.064(\text{stat}) \pm 0.055(\text{stat}))\%$, 3.6 standard deviations away from the SM. Regarding this measurement, in Ref. [38] the interesting observation

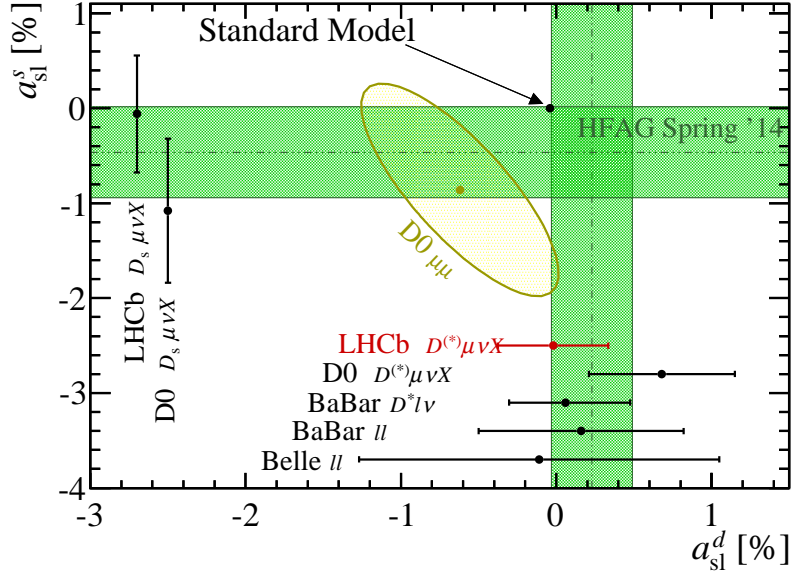


Figure 2: Overview of the measurements of the CP asymmetry in mixing of $B_{d,s}$ mesons. The preliminary measurement from the BaBar collaboration, $a_{sl}^d = (-3.9 \pm 3.5(\text{stat}) \pm 1.9(\text{syst})) \cdot 10^{-3}$ [36, 37], presented at this conference, is included and considered in the average. The bands correspond to the average of the pure a_{sl}^d and a_{sl}^s measurements, which are in conflict with the D0 dimuon result.

has been made that not only the flavour-specific CP asymmetries contribute, but also mixing-induced CP asymmetries, contributing proportional to $\Delta\Gamma_q$. A more detailed analysis [18] shows that the effect is about 50% smaller than estimated in Ref. [38], yielding a *larger* tension than quoted above. While this effect does have an influence on the LSDA, it seems too small to explain the measurement within the SM, thereby still hinting at a NP explanation. However, even in NP models it is rather difficult to achieve a large enhancement without violating other constraints. Interestingly, many constraints can be avoided using the fact that the dependence on the individual contributions to Γ_{12} is different for the LSDA, the flavour-specific CP asymmetry, and $\Delta\Gamma$ [18]. One class of models where an enhancement is related to a potential non-

unitarity of the CKM matrix has been discussed in [19, 39] and references therein. However, also here the enhancement is limited, especially by the constraints from V_{ub} and $S_{\text{CP}}(B_s \rightarrow J/\psi\phi)$, yielding values of at most 10^{-3} for the LSDA.

3 Determination of the mixing phases $\phi_{d,s}$

The precision extractions of the mixing phases $\phi_{d,s}$ aim at the precise knowledge of these SM parameters, but more importantly the discovery of potential NP contributions. These phases can be cleanly determined in tagged time-dependent analyses of $b \rightarrow c\bar{c}s$ transitions [40]. The advantage of this class of decays is that the amplitude is dominated to good approximation by its contribution proportional to $\lambda_{cs} \equiv V_{cb}V_{cs}^*$, while the subleading parts, usually jointly dubbed *penguin pollution*, are not only CKM-suppressed by $\lambda_{us}/\lambda_{cs} \approx 2\%$, but are also expected to have smaller hadronic matrix elements; however, this latter suppression is hard to quantify for the decays in question. With the time-dependent CP asymmetry of a decay \mathcal{D} into a CP eigenstate given as

$$a_{\text{CP}}(\mathcal{D}; t) \equiv \frac{\Gamma(\mathcal{D}; t) - \Gamma(\bar{\mathcal{D}}; t)}{\Gamma(\mathcal{D}; t) + \Gamma(\bar{\mathcal{D}}; t)} = \frac{S_{\text{CP}}(\mathcal{D}) \sin(\Delta mt) - C_{\text{CP}}(\mathcal{D}) \cos(\Delta mt)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}(\mathcal{D}) \sinh(\Delta\Gamma t/2)}, \quad (3)$$

the corrections of the resulting (schematic) relations

$$S_{\text{CP}}(B_{d,s} \rightarrow J/\psi X) \simeq \pm \sin \phi_{d,s}, \quad C_{\text{CP}}(B_{d,s} \rightarrow J/\psi X) \simeq 0, \quad (4)$$

are estimated to be of the order $\mathcal{O}(10^{-3})$, only [41]; it is, however, notoriously difficult to actually calculate the relevant matrix elements, and non-perturbative enhancements cannot be excluded. Given the absence of large NP effects, as inferred already *e.g.* from Refs. [2, 3, 31], but for the decays in question also from the compatibility of the recent measurements [42, 43, 44] with the SM, only the quantitative control of these subleading contributions will allow to fully exploit the precision measurements from the LHC experiments and Belle II.

To gain control over these contributions, typically flavour-symmetry relations are used, where the unknown matrix elements can be extracted from data. When using the U -spin subgroup of $SU(3)$, relating down and strange quarks, usually one “control mode” is used, where the relative influence of the penguin matrix elements is larger [45, 46, 47, 48]. Experimentally, the disadvantage of these modes is that their rates are suppressed by $\lambda^2 \sim 5\%$. Theoretically, there are mainly two difficulties: firstly, since only one additional mode is used, it is not possible to control penguin pollution and U -spin breaking contributions simultaneously. The necessary assumption for the latter can lead to a bias in the extraction of the penguin shift [49, 50]. Secondly, for $B_s \rightarrow J/\psi\phi$, the control modes involve matrix elements of octet final states, while

the ϕ is a superposition of octet and singlet. The first issue has been addressed for the extraction of ϕ_d in Ref. [50] by extending the flavour symmetry to the full $SU(3)$ group, thereby including a full set of control modes. The additional data allow to control the penguin shift and $SU(3)$ -breaking contributions at the same time model-independently. The second issue has been estimated to be a small effect [51], but an extraction from data should be aimed for, which might be possible using the corresponding final states with the ω meson. The control of both effects seems therefore feasible in the future, allowing for precision extractions of $\phi_{d,s}$ even beyond the present level.

A new estimate for the penguin pollution in $B_d \rightarrow J/\psi K$ and $B_s \rightarrow J/\psi \phi$ has been presented at this workshop [52, 53]. Here it has been shown that the up-quark penguin contribution can be described in an effective theory, resulting from an additional OPE in $1/q^2$ with $q^2 \sim M_{J/\psi}^2$. This approach is again limited by the insufficient knowledge of the corresponding hadronic matrix elements; estimating them in the $1/N_C$ approach, where $N_C = 3$ is the number of colours, an upper limit of $\Delta\phi_{d,s} \lesssim 1^\circ$ is obtained, consistent with the limits obtained from flavour symmetries described above.

Apart from the “golden” modes, $B_d \rightarrow J/\psi K_S$ and $B_s \rightarrow J/\psi \phi$, also the $B_s \rightarrow J/\psi f_0(980)$ decay was proposed to extract ϕ_s [54], $f_0(980)$ being the largest resonance in $B_s \rightarrow J/\psi \pi^+ \pi^-$; since it is a scalar meson, this mode has the advantage that no angular analysis is necessary, yielding a sensitivity similar to $B_s \rightarrow J/\psi \phi$. Of concern in this case is the hadronic nature of the $f_0(980)$, which has untypical characteristics for a simple $q\bar{q}$ meson (see *e.g.* Ref. [55] for recent reviews), and its mixing with the $\sigma(f_0(500))$ resonance. Importantly, the hadronic features influence the decay dynamics, and specifically the penguin contributions [56]. This renders a control-mode analysis of the type described above more complicated. In Ref. [57] a pure tetraquark interpretation was excluded under the assumption of a vanishing mixing angle between $f_0(980)$ and σ . Dropping this assumption and re-examining earlier constraints could re-open this possibility [58]. In any case the hadronic nature of the $f_0(980)$ remains an open issue and the control of subleading contributions to a comparable level as in $B_s \rightarrow J/\psi \phi$ seems hard to achieve.

Experimentally, the decay mode $B_s^0 \rightarrow J/\psi \phi$ is not only used to measure ϕ_s , but also $\Delta\Gamma_s$ and Γ_s . A time-dependent analysis is necessary to separate the CP-odd and CP-even components in this decay, as also discussed at this conference [59, 60, 61]. The experimental techniques are very similar across the three experiments ATLAS, CMS, and LHCb, using an unbinned maximum likelihood. The fits are multi-dimensional, including for example the invariant mass of the $J/\psi \phi$ system, the decay time and the 3 angles in the helicity basis (LHCb) or transversity basis (CMS, ATLAS). In all cases, flavour algorithms based on different taggers like the same-side Kaon tagger at LHCb and the opposite-side lepton tagger at CMS and ATLAS are used to identify the flavour of the B_s^0 meson when it was produced in the LHC

Exp.	ϕ_s/rad	$\Delta\Gamma_s/\text{ps}^{-1}$	Comments
ATLAS	0.12(25)(11)	0.053(21)(9)	$B_s^0 \rightarrow J/\Psi KK$, $ \lambda \equiv 1$ 4.9 fb $^{-1}$, [59, 43]
CMS	-0.08(10)(3)	0.095(13)(7)	$B_s^0 \rightarrow J/\Psi KK$, $ \lambda \equiv 1$, 20.0 fb $^{-1}$ [60, 44]
LHCb	0.07(9)(1)	0.100(16)(3)	$B_s^0 \rightarrow J/\Psi KK$, $ \lambda = 0.94(3)(2)$, 1 fb $^{-1}$ [61, 62]
LHCb	0.07(7)(1)	—	$B_s^0 \rightarrow J/\Psi \pi\pi$, $ \lambda = 0.89(5)(1)$, 3 fb $^{-1}$ [61, 63]

Table 2: Recent results for the mixing phase ϕ_s and width difference $\Delta\Gamma_s$. The two uncertainties given are first the statistical and then the systematic one.

collisions.

The results from these analyses are collected in Table 2.[‡] The $B_s \rightarrow J/\Psi KK$ analyses are focussed on the $B_s \rightarrow J/\Psi(\rightarrow \mu\mu)\phi(\rightarrow KK)$ chain. Regarding $B_s \rightarrow J/\Psi\pi\pi$, a full amplitude analysis was done by the LHCb experiment to establish that the CP content of this channel is mainly CP-odd [63]. This fraction was found to be higher than 97.7% at 95% confidence level (CL). Nevertheless, an angular analysis was used to include even this small CP-even fraction precisely.

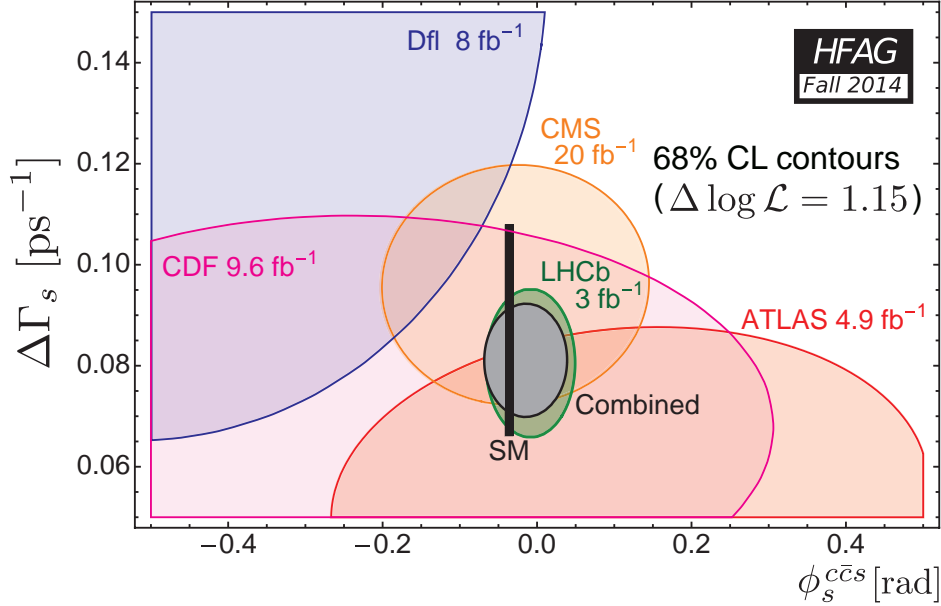


Figure 3: Combination of the results for $\phi_s^{c\bar{c}s}$ vs. $\Delta\Gamma_s$ from various experiments.

The individual results and their average are displayed in Fig. 3, showing good consistency. While the statistical uncertainty of ϕ_s is still much larger than the one of the SM prediction, penguin pollution could already play a significant role. In

[‡]A couple of months after the CKM workshop, LHCb updated their $B_s \rightarrow J/\Psi KK$ measurement using the full dataset collected during run 1. The results can be found in Ref. [42]

that respect there has been experimental progress as well, with measurements of the branching ratios of $B_s^0 \rightarrow J/\Psi K_S^0$ and $B_s^0 \rightarrow J/\Psi K^*$, together with polarization fractions and CP-violating parameters for the latter by the LHCb collaboration [61, 64, 65, 66]. These modes can be used as control modes for $B^0 \rightarrow J/\Psi K_S^0$ [47] and $B_s^0 \rightarrow J/\Psi^0 \phi$ [48], respectively, using $SU(3)$ and, in the case of $B_s \rightarrow J/\Psi K^*$, additional dynamical assumptions.

Another theoretically very clean mode sensitive to ϕ_s is $B_s^0 \rightarrow D_s^+ D_s^-$, providing an independent means to access this phase. Also here no angular analysis is necessary, but experimentally the charmonium modes are easier to access. The penguin pollution in this mode is again very difficult to calculate theoretically, but can be controlled with the means described above for the golden modes: the early proposal to use U -spin [45] has been extended to a full $SU(3)$ analysis [27], presented at this conference [67], allowing to control symmetry-breaking contributions model-independently. Additionally, $B^0 \rightarrow D^{(*)} D^{(*)}$ decays allow for various other NP tests, for example with quasi-isospin sumrules for branching ratios, and provide insights into QCD dynamics, like for instance weak annihilation [67, 27].

The LHCb collaboration has measured the time-dependent CP asymmetry in $B_s^0 \rightarrow D_s^+ D_s^-$ for the first time, using $\Delta\Gamma_s$, Γ_s and Δm_s as external constraints [68, 69]. This constitutes the first measurement of ϕ_s using a purely hadronic final state. Using the full run 1 dataset, they report:

$$\phi_s = 0.02 \pm 0.17_{\text{(stat)}} \pm 0.02_{\text{(syst)}} \quad \text{and} \quad |\lambda| = 0.91_{-0.25}^{+0.18}_{\text{(stat)}} \pm 0.02_{\text{(syst)}}, \quad (5)$$

where the correlation between ϕ_s and λ is 3 %. Within the still sizable uncertainties this result is consistent with SM expectations.

The most recent analysis from the BaBar experiment of the decay mode $B^0 \rightarrow D^{*+} D^{*-}$ [70] was also presented at this conference [71]. This study uses the partial reconstruction technique, where one of the final state mesons is fully reconstructed, while only the slow pion from the decay of the second $D^{*\pm}$ meson is used. Neglecting the penguin contribution, which is a good approximation at this level of precision, the following CP-violating parameters are obtained:

$$\begin{aligned} C_{\text{CP},+} &= +0.15 \pm 0.09_{\text{(stat)}} \pm 0.04_{\text{(syst)}}, \\ S_{\text{CP},+} &= -0.49 \pm 0.18_{\text{(stat)}} \pm 0.07_{\text{(syst)}} \pm 0.04. \end{aligned}$$

The third uncertainty for the $S_{\text{CP},+}$ term is due to the input value of the CP-odd fraction, fixed to $R_{\perp} = 0.158 \pm 0.029$, which is necessary to extract from the effectively measured parameters S_{CP} and C_{CP} , which involve admixtures of CP eigenstates, the ones for the CP eigenstates which obey Eq. (4) when neglecting penguin pollution. These results are consistent with SM expectations as well as previous measurements.

Other processes sensitive to $\phi_{d,s}$ are $b \rightarrow s\bar{q}q$ transitions of $B_{d,s}$ mesons, where q is a light quark. These modes are dominated by penguin contributions in the SM,

leading again to Eq. (4). Corrections to this relation are largely calculable in QCD factorization and have been estimated in Ref. [72]. The induced shifts are larger than for $b \rightarrow c\bar{c}s$ transitions, since they are determined by the ratio of the “pollution” and the leading amplitude which is suppressed. For the same reason the sensitivity to NP contributions is generically larger for these modes, which constitutes the main interest in them.

At this workshop several analyses for this class of modes have been presented by the Belle collaboration [73, 74, 75], namely time-dependent measurements for $B^0 \rightarrow \omega K_S$, $B^0 \rightarrow \eta' K^0$ and $B^0 \rightarrow \eta K_S \gamma$.

In the decay mode $B^0 \rightarrow \omega K_S^0$ the increased statistics of the full Belle dataset and improved reconstruction efficiency allowed to obtain evidence for CP violation for the first time in this mode: the result reads [74] $A_{\text{CP}} \equiv -C_{\text{CP}} = -0.36 \pm 0.19 \pm 0.05$ and $S_{\text{CP}} = +0.91 \pm 0.32 \pm 0.05$, which is 3.1σ away from the zero-CP-violation point and consistent with the SM expectation.

The decay mode $B^0 \rightarrow \eta' K^0$ includes two CP-eigenstates, the CP-even $B^0 \rightarrow \eta' K_S$ and the CP-odd $B^0 \rightarrow \eta' K_L$. In total, 3541 ± 91 signal events are reconstructed in both decay modes. The obtained results are consistent and are combined to yield the most precise measurement in this decay mode so far, $A_{\text{CP},f} = +0.03 \pm 0.05 \pm 0.04$ and $-\xi_f S_{\text{CP},f} = +0.68 \pm 0.07 \pm 0.03$, where ξ_f is the CP-eigenvalue of the corresponding final state [75]. Again, no significant deviation from the SM expectation is observed.

Finally, an attempt is made to find CP violation in the decay mode $B^0 \rightarrow \eta K_S \gamma$, however, no significant signal is observed.

4 Determination of the UT angles $\alpha(\phi_2)$ and $\gamma(\phi_3)$

Similarly to the UT angle $\beta(\phi_1)$ the angle α can be extracted from interference in $B^0(\bar{B}^0)$ decays, but using $b \rightarrow d\bar{u}u$ transitions, specifically $B \rightarrow \pi\pi, \pi\rho, \rho\rho$ decays. If these were pure tree decays, they would be directly sensitive to the combination $\phi_d + 2\gamma \stackrel{\text{SM}}{=} 2\pi - 2\alpha$. However, due to the different hierarchy of the CKM matrix elements in $b \rightarrow d$ transitions the “penguin pollution” of these modes is much more significant than for $b \rightarrow s\bar{c}c$ transitions, and has to be taken into account from the beginning. To disentangle the penguin and tree contributions, usually an isospin analysis is carried out in $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ [76], relating the modes $\bar{B}^0 \rightarrow h^+h^-$, $\bar{B}^0 \rightarrow h^0h^0$ and $B^- \rightarrow h^-h^0$ via $A^{+-}/\sqrt{2} + A^{00} = A^{+0}$, which can be presented as a triangle in the complex plane. The full information about the relative size and (relative) phase of each amplitude can be extracted by measuring the corresponding rates and CP asymmetries.

The Belle experiment presented updated analyses for several of the relevant modes at this conference, namely $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow \pi^0\pi^0$ and $B^0 \rightarrow \rho^0\rho^0$ [77]. The first one has a large branching fraction and high reconstruction efficiency, which allowed

to reconstruct 2964 ± 88 signal events and to perform a time-dependent measurement, yielding the most precise values of the CP-violation parameters to date:

$$S_{\text{CP}} = -0.64 \pm 0.08(\text{stat}) \pm 0.03(\text{syst}) \quad \text{and} \quad C_{\text{CP}} = -0.33 \pm 0.06(\text{stat}) \pm 0.03(\text{syst}). \quad (6)$$

The branching ratio for $B \rightarrow \pi^0 \pi^0$ is discussed in more detail in the summary of WG III [78]; it is worth pointing out that the new result, $BR(B^0 \rightarrow \pi^0 \pi^0) = (0.90 \pm 0.12 \pm 0.10) \times 10^{-6}$, is significantly smaller than the previous Belle result [79] and shows a $\sim 3\sigma$ tension with the BaBar one [80]. It is however much closer to the theoretical prediction from QCD factorization [81], thereby indicating a solution for a long-standing puzzle.

For the decay mode $B^0 \rightarrow \rho^0 \rho^0$ a 3.4σ signal is observed by Belle, which corresponds to the branching fraction of $(1.02 \pm 0.30 \pm 0.15) \times 10^{-6}$. This result is used together with results from BaBar and Belle for the other $B \rightarrow \rho\rho$ modes to obtain the value $\alpha|_{\rho\rho} = (89.9^{+5.4}_{-5.3})^\circ$ [2].

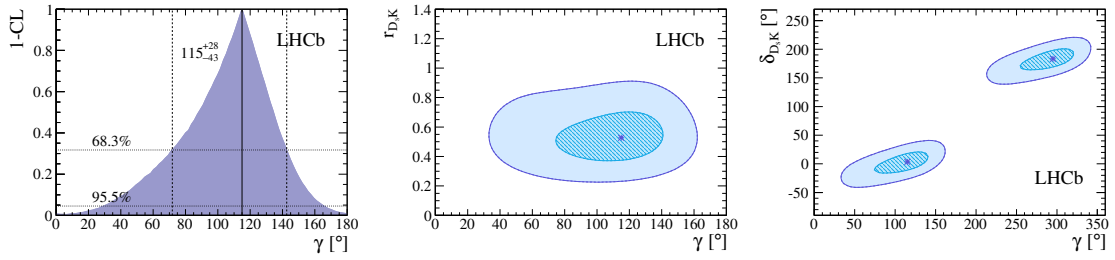


Figure 4: The SM-like solution for γ from $B_s \rightarrow D_s K$, together with the central value and the 68.3% CL interval (left). Profile likelihood contours of $r_{D_s K}$ vs. γ (middle), and δ vs. γ (right). The contours are at 1σ (2σ), corresponding to 39% CL (86% CL) in the Gaussian approximation. The markers denote the best-fit values.

The weak phase γ remains the angle in the unitarity triangle with the largest uncertainties. So far it has been measured with time-independent methods using $B^{0/+}$ decays collected at the B -factories and the LHCb experiment, discussed in detail in the summary of WG III [78]. The focus here is on the time-dependent analysis of $B_s^0 \rightarrow D_s^\mp K^\pm$ [82], carried out for the first time using 1 fb^{-1} collected by the LHCb experiment [83]. The final state is accessible from both B_s and \bar{B}_s which makes it sensitive to the combination $\phi_s + \gamma$ via the CP-violating observables $C_{\text{CP},f}$, $A_f^{\Delta\Gamma}$, $A_{\bar{f}}^{\Delta\Gamma}$, $S_{\text{CP},f}$ and $S_{\text{CP},\bar{f}}$, see Ref. [83] for further details. Using the measurement of ϕ_s discussed in the previous section, these observables allow for the determination of the weak phase $\gamma = (115^{+28}_{-43})^\circ$, the strong phase difference between the B_s and \bar{B}_s decay $\delta = (3^{+19}_{-20})^\circ$ and the ratio of the absolute values of these amplitudes, $r_{D_s K} = 0.53^{+0.17}_{-0.16}$, as shown in Fig. 4. The phases are extracted with a two-fold ambiguity, the values quoted here correspond to the SM-like solution.

5 Conclusions

The B factories, Tevatron and LHC experiments have established the validity of the Kobayashi-Maskawa mechanism of CP violation to an unexpected high level of precision; at the moment the global picture is beautifully consistent, with very few exceptions. This situation requires the control of uncertainties at an unprecedented level, posing new challenges for experiments and theory alike. Nevertheless, the prospects for continued progress are excellent, as explicitly discussed in Refs. [5, 6, 59, 60, 84, 85, 86] and furthermore visible in the theory strategies presented at this workshop. Experimentally, the recently started Run II of the LHC will dominate during the time until the next CKM workshop. While some of the measurements are met already with corresponding theory uncertainties at an appropriate level, see *e.g.* the table in Ref. [84], others require progress in Lattice QCD, the prospects of which have been discussed in Ref. [87], or other non-perturbative methods, as discussed *e.g.* in Sec. 3. This combined effort visible at this workshop has the potential to finally allow for a first glimpse of what lies beyond the SM.

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